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DIRECT TENSION TEST RESULTS FOR SOME ASPHALT CONCRETES

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PURDUE UNIVERSITY
INDIANA STATE HIGHWAY COMMISSION

Technical Paper

DIRECT TENSION TEST RESULTS FOR SOME ASPHALT CONCRETES

TO: J. F. McLaughlin, Director
Joint Highway Research Project

March 16, 1976

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FROM: H. L. Michael, Associate Director
Joint Highway Research Project

Project: C-36-6Y

Attached is a Technical Paper titled "Direct Tension Test Results for Some Asphalt Concretes" by R. D. Pavlovich and W. H. Goetz. The paper is from the Final Report on the HPR Part II Research Study "Cracking in Bituminous Mixtures". That Final Report was titled "Limiting Strain as a Failure Criterion for Bituminous Mixtures".

The authors presented the paper at the Annual Meeting of the Association of Asphalt Paving Technologists in New Orleans February 16-18, 1976. The paper is also planned for publication and approval of such publication by the JHRP Board in accord with our policy as requested.

The paper will also be forwarded to FHWA and ISHC for information as the Final Report has been accepted.

Respectfully submitted,

Harold L. Michael

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16. Abstract

This paper describes an experiment that determined the effect of some mixture and environmental variables on strain at failure (limiting strain) of some asphalt concretes. Cylindrical specimens were loaded to failure in direct tension and strain at failure was calculated from axial deformations.

Independent variables of the experiment included asphalt type as described by nominal penetration and viscosity, aggregate gradation, temperature and strain rate. Analysis of variance was used to evaluate the effect of each of these parameters on limiting strain. Linear and non-linear regression equations are provided to relate the significant independent variables to limiting strain.

Analysis of these data (or combinations of these data for each sequential step) resulted in the following conclusions:

1. Asphalt types that were used for this study have no significant effect on limiting strain when mixtures using these materials are loaded to failure in direct tension.
2. Fine-graded mixtures exhibit significantly greater strain at failure than dense- or coarse-graded mixtures.
3. Temperature is, by far, the most significant factor, of the parameters studied, affecting limiting strain.
4. Strain rate, as should be expected for a viscoelastic material, has an effect on limiting strain.
5. Reasonable agreement between the values predicted by the Van der Poel nomograph and measured stiffness values was observed for most specimens tested.

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by

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Purdue University
and the
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INTRODUCTION

Several thickness design and analysis techniques that have recently been made available utilize tensile strain as part of the procedure (1, 2, 3, 4). The study described in this paper determines the effect of some mixture and environmental variables on strain at failure (limiting strain) for some asphalt concretes.

Cylindrical specimens were loaded to failure in direct tension (see Figure D4), and strain at failure was calculated from axial deformations.

Data generated by this study are intended to be used in at least two ways. First, this information can be used to establish working values for rational mixture and thickness designs for mixtures where experimental and field parameters are essentially the same. Secondly, these fundamental data can be used to correlate direct tension values with those that are obtained with simpler indirect tension test methods (8).

EXPERIMENT PARAMETERS

Independent variables of the experiment included asphalt type, as described by nominal penetration and viscosity, aggregate gradation, temperature and strain rate.

Analysis of variance (ANOVA) was used to evaluate the effect of each of these parameters on limiting strain. Linear and non-linear regression equations are provided to relate the significant independent variables to limiting strain.

Levels of the independent variables are as follows:

1. Asphalt type at six levels. These include three nominal penetration grades, 60-70, 85-100, and 120-150. Within each

penetration grade, a relatively high and low viscosity material is included. Properties of the test asphalts as well as fingerprint data are shown in appendix A.

2. Aggregate gradation at three levels; one hundred percent crushed limestone was used for relatively coarse, dense, and fine gradations. Gradation curves and other aggregate data are shown in appendix B.
3. Temperatures were controlled at six levels; 140 F (60 C), 108.5 F (42.5 C), 77 F (25 C), 45.5 F (7.5 C), 14 F (-10 C) and -17.5 F (-27.5 C).
4. Four levels of strain rate were intended to be controlled for the experiment. An upper limit of 159 microstrain per second and a lower limit of 0.3 microstrain per second with two equally spaced intermediate strain rates were attempted. This upper limit is approximately a rate equivalent to a design highway vehicle moving at the speed limit or a design aircraft at takeoff, whereas the lower limit is approximately equivalent to a long term temperature change. Strain rate could not be controlled without extensive modification of the electrohydraulic loading equipment used for the study but strain rate was included in the analysis as an uncontrolled variable.

DESIGN OF THE EXPERIMENT

An ideal full factorial experiment using three replications of each possible combination of all independent variables requires 1296 specimens. Both time and material economy precluded the use of this

full factorial experiment. Rather than arbitrarily reduce the replications or remove some levels of the independent variables, the following sequential experiment was designed.

1. Perform an exploratory run at a single temperature of 77 F (25 C) and include all mixture types to evaluate the effect of mixture variables.
2. After the exploratory portion was analyzed, make a second run using a single mixture type at each level of temperature to evaluate temperature effects.
3. Based on analysis of both of the above runs, a final factorial was completed that would utilize some additional treatment combinations. All data generated in each of the phases would be included in the final analysis.

MIXTURE PROPERTIES

Three mixture gradations were used for each of the six asphalts. Design asphalt content was determined by the Hveem method as described by The Asphalt Institute (5).

Mixture designation is by a combination of numbers and letters that represents nominal penetration, relative viscosity and gradation. The first number (6, 8 or 12) identifies nominal penetration of the asphalt as 60-70, 85-100 or 120-150; the first letter (H or L) identifies relative viscosity of the asphalt as high or low, and the second letter (C, D or F) identifies the mixture gradation as coarse, dense or fine. Hence, a mixture designated, say, as 12LD consists of 120-150 nominal penetration grade asphalt cement of relatively low viscosity and a dense aggregate gradation.

A summary of physical properties of each mixture is included in appendix C.

EXPERIMENT SET-UP

Specimen Fabrication

Four-inch diameter by approximately 8-inch high cylindrical specimens were compacted with a California kneading compactor. Preliminary compaction was accomplished by introducing a 1200 gram batch into the mold in a steady stream from a circular trough while the compacting foot was applying 250 psi tamps. This first lift was subjected to 30 tamps and the foot was allowed to "walk-out" of the mixture. This procedure was repeated for each of two more lifts of approximately 1200 grams each. Finally, the specimen was subjected to 150 tamping blows at 500 psi foot pressure.

After kneading compaction, specimens were oven cured in their molds for 90 minutes at 140 F (60 C). After curing, a 12,560 lb leveling load was applied by the double plunger method at a head speed of 0.05 in. per min. with a mechanical testing machine.

After cooling to room temperature, specimens were removed from their split cylinder molds and bulk density was determined in accordance with ASTM D 2776. Specimen uniformity was checked by comparing specimen density with densities as determined during mix design.

Specimen Capping

After mold removal and density determinations were completed, approximately one and one half inch of material was removed from the top of the specimen with a diamond bladed masonry saw. This operation removed aggregate particles that may have fractured during compaction,

provided a clean surface for capping, and insured end surfaces that were perpendicular to the specimen axis.

Steel caps were fastened to each end of the specimen with a rigid formulation of a two-part epoxy. Adhesive was Thermoset 103 as supplied by Thermoset Plastics, Inc. of Indianapolis, Indiana.

A vertical alignment jig was used to insure that both caps were perpendicular to and concentric with the specimen axis.

A cap detail is shown in appendix D.

Deformation Measurements

Axial deformations were measured by means of an extensiometer clamped to the specimen. This system was used to measure deformation of the specimen directly without requiring corrections for movement of the adhesive, caps, connecting system, or testing machine actuator rods.

Extensiometer transducers were a pair of LVDT's with self-contained signal conditioning circuitry. Details of the extensiometer are shown in appendix D.

Specimen deformation was considered to be the mean value of the two LVDT deformations. Strains were calculated from this deformation and gage length of the extensiometer.

Loading System

Loads were applied to the specimen by means of an electro-hydraulic closed loop testing machine in stroke control. The function generator of this machine was modified by installing a one million second analog convertor. This device provides a slower ram movement and hence a slower strain rate than the conventional pump and ram system combination will normally provide.

Data Readout

Voltage from the load cell of the testing machine and LVDT's during the test were monitored by a scanning voltmeter and printed on tape. These data were reduced to provide stress-strain-time relationships for analysis.

Temperature Control

A large conditioning unit was fabricated that included both heating and refrigerating units. Conditioned air from this unit was moved through pipe ducts to a temperature control chamber mounted on the testing machine frame. This device was capable of maintaining $\pm$0.5 F for periods of up to four hours and $\pm$1.0 F for longer periods.

EXPERIMENT RESULTS AND ANALYSIS OF DATA

Cell designations (a given combination of mixture type and test temperature), number of observations per cell and cell means are shown in Table 1. Cell standard deviations are shown in Table 2.

For all analyses that follow, homogeneity of variance was checked prior to making calculations for analysis of variance. Validity of the assumption of homogeneity was tested by the q-test of Burr and Foster and the guidelines of Anderson and McLean (6) were followed in accepting or rejecting homogeneity of the raw data. In cases where variance of the raw data was not accepted as homogeneous, appropriate transformations were applied before making the analysis of variance (ANOVA).

Exploratory Experiment

To examine the effect of mixture type, results were analyzed for tests run at 77 F (25 C). This experiment includes eight mixture types in cells G, I, D, G, H, J, K, and L. In the case of cell D, four values of 4770, 4591, 3814, 3919 were used. Table 3 is ANOVA for these data.

From this analysis, mixture type is significant at the 5 percent level, but not at the 1 percent level. Further examination of these data by use of Newman-Keuls test on the means shows no significant differences at the 1 percent level. At the 5 percent level, only one pair was significant. The mean for 8LF (cell K) was greater than 12LD (cell H).

It should be noted that mixture type includes all asphalts of both high and low viscosity and all gradations, but not all of the possible combinations. It was reasoned that the trend of values for limiting strain would be the same for the fine and coarse gradations using the various asphalts as were measured for the dense gradation.

It was concluded that asphalt viscosity and penetration have no significant effect at a test temperature of 77 F (25 C).

To further examine the effect of mixture type, with the viscosity parameter eliminated, tests at the relatively low viscosity for each asphalt were run at -17.5 F (-27.5 C) and 108.5 F (42.5 C) and these data were analyzed along with those of the 77 F (25 C) runs. The cells included in this analysis are shown in Table 4 and the ANOVA of the square root transformed data are shown in Table 5.

This analysis shows that the only significant factor is temperature and that it is highly significant. Mixture type has no significant effect.

Examination of the mixture composition of the last experiment shows three dense graded and two non-dense graded aggregates. Because of the possibility of an effect due to gradation, as shown by the exploratory one-way classification, it was decided to perform an analysis of the data based on gradation and temperature and to include a set of tests at 140 F (60 C). Cells included in this analysis are shown in Table 6 and the ANOVA of the cube root transformed data are shown in Table 7.

This analysis shows that gradation is significant at the 1 percent level and cell means of the transformed data show that fine graded mixtures have larger values of limiting strain than do the dense and coarse graded mixtures.

Final Experiment

Cells included in the final analysis are shown in Table 8. The reason that all data taken and shown in Table 1 are not included in this analysis is that the computer program used to run the two-way analysis of variance, which was the only appropriate program available at the time of this study, will not run if empty cells exist. ANOVA of the fourth root transformed data are shown in Table 9.

This analysis shows that the temperature effect is highly significant and that mixture type is significant at the five percent level but not at the one percent level.

REGRESSION EQUATIONS

In order to estimate limiting strain value, as is generally necessary for analytical solutions, it was considered desirable to generate regression equations to provide these estimators. Several regressions

relating limiting strain or some function of limiting strain to temperature and strain rate (approximately 20 combinations) were evaluated. The most reliable predictors are shown here. Predictive capability of each equation was judged on the basis of cumulative R^2 as well as by superimposing a plot of the equation on a plot of the 95 percent confidence limits of limiting strain for each temperature.

Symbols for Regression

$\hat{\varepsilon}_f$ = estimated limiting strain in microinches per inch (microstrain).

T_F' = shifted temperature in degrees Fahrenheit and is calculated as $T_F' = T_F + 20.0$ where T_F is the actual test temperature. The reason for using this shifted temperature is that the computer cannot extract the even root of a negative number such as -17.5 F.

$\dot{\varepsilon}$ = mean strain rate during the test in microstrain per second.

β_i = regression coefficient.

e = error term.

Equation Without Strain Rate

Case I:

$$\hat{\varepsilon}_f = \beta_0 + \beta_1 (T_F') + \beta_2 (T_F')^2 + \beta_3 (T_F')^3 + e$$

Case II:

$$\sqrt[4]{\hat{\varepsilon}_f} = \beta_0 + \beta_1 (T_F') + \beta_2 (T_F')^2 + \beta_3 (T_F')^3 + e$$

Regression coefficients and R^2 for Case I are shown in Table 10. Table 11 shows these values for Case II. Plots of Cases I and II are shown on Figures 1 and 2.

Equations With Strain Rate

Case III:

$$\hat{\varepsilon}_f = \beta_0 + \beta_1\dot{\varepsilon} + \beta_2\dot{\varepsilon}^2 + \beta_3\dot{\varepsilon}^3$$

$$+ \beta_4 T_F' + \beta_5(T_F')^2 + \beta_6(T_F')^3$$

$$+ \beta_7\dot{\varepsilon}T_F' + \beta_8(\dot{\varepsilon}T_F')^2 + \beta_9(\dot{\varepsilon}T_F')^3 + e$$

Case IV:

$$\sqrt[4]{\hat{\varepsilon}_f} = \beta_0 + \beta_1\dot{\varepsilon} + \beta_2\dot{\varepsilon}^2 + \beta_3\dot{\varepsilon}^3$$

$$+ \beta_4 T_F' + \beta_5(T_F')^2 + \beta_6(T_F')^3$$

$$+ \beta_7\dot{\varepsilon}T_F' + \beta_8(\dot{\varepsilon}T_F')^2 + \beta_9(\dot{\varepsilon}T_F')^3 + e$$

Regression coefficients and R^2 for Cases III and IV are shown in Table 12.

Comparing Case III with the cubic fit of Case I, it is seen that no significant increase in R^2 is effected by introducing strain rate into the regression. Likewise, when considering the fourth root function of limiting strain, and comparing cumulative R^2 values for Case IV with Case II values, it is seen that no significant increase in R^2 is effected by introducing strain rate.

This is not to imply, however, that strain rate has no effect. This effect can only be evaluated by a controlled experiment that requires equipment that was not available at the time of the study.

Nonlinear Regressions

Case V:

$$\varepsilon_f = B_0 + B_1(T_F') + B_2(T_F')^2 + B_3(T_F')^3$$

Case VI:

$$\varepsilon_f = \frac{\text{Exp } [1/2(T'_F - B_1)^2 \div B_2]}{\sqrt{2\pi \; B_3}}$$

Case VII:

$$\varepsilon_f = \frac{[B_1(T'_F - B_2)^2 \div B_3]}{\sqrt{\pi \; B_4}}$$

Coefficients for these cases are shown in Table 13 and plots are shown on Figure 3.

COMPARISON BETWEEN CALCULATED AND MEASURED STIFFNESS

Stiffness values were computed for several time points for each specimen using the Van der Poel nomograph to calculate asphalt stiffness and then calculating mixture stiffness based on asphalt stiffness and volume concentration of aggregate (7). Results of comparing 426 points on 90 specimen stiffness curves are shown in Table 14. Comparison of theoretical and calculated values are reasonably good considering that Van der Poel considers the asphalt stiffness nomograph to be accurate within a factor of 2. Also, the asphalt to mixture conversion assumes a void content of three percent whereas mixtures for this study contain slightly more than four percent voids. Volume concentration of aggregates for this study is approximately 0.9 whereas the theoretical values are based on a range of 0.7 to 0.9

CONCLUSIONS

Based on the work described, the following conclusions are drawn:

1. Temperature is, by far, the most significant factor of the parameters studied affecting limiting strain. Limiting strain at 140 F (60 C) is approximately 300 to 500 times as great as that at -17.5 F (-27.5 C).

2. Strain rate, as should be expected for a viscoelastic material, has an effect on limiting strain. However, the effect of strain rate, resulting from large variation in speed of ordinary vehicular loadings is equivalent to the effect of only a few degrees of temperature change. That is, a small change in temperature affects limiting strain much more than does a large change in vehicle speed.

3. Fine graded mixtures have a somewhat greater value of limiting strain for a given temperature and strain rate than do coarser graded mixtures.

4. Within the range of asphalts used for this study, asphalt type has no significant effect on limiting strain as measured by direct tension testing. It should be noted that the test asphalts included the normal range of penetration and viscosity grades generally used for asphalt concretes in the United States, but they did not include the full range of penetration and penetration indices available.

5. Finally, stiffness values that relate stress to strain for a given asphalt, temperature, loading time and aggregate volume as determined by the Van der Poel nomograph and modified for aggregate content were reasonably well verified.

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APPENDIX A
ASPHALT DATA

TABLE A1
ASPHALT PHYSICAL PROPERTIES AND SPECIFICATION COMPLIANCE RESULTS

Penetration (ASTM D5)

Sample	100g., 5 Sec. 77 F (25 C)	100g., 5 Sec. 60 F (15.6 C)	100g., 5 Sec. 32 F (0 C)	200g., 60 Sec. 32 F (0 C)
6H	60	23	6	18
6L	54	18	1	11
8H	73	34	6	23
8L	86	31	5	16
12H	104	50	10	34
12L	119	43	6	23

Viscosity (ASTM D2171)

Sample	(Absolute (30cm. Hg.) (Poises) 100 F (37.8 C)	140 F (60.0 C)	180 F (82.2 C)	Kinematic (Centistokes) 205 F (96.1 C)	275 F (135 C)	350 F (176.7 C)
6H	177,000	3970	244	6680	500	89.0
6L	101,000	2060	146	3830	373	67.0
8H	93,500	2550	184	4780	492	89.4
8L	43,700	1200	86.8	2700	276	54.6
12H	36,400	1330	115	3300	361	71.2
12L	23,100	734	59.3	1960	226	48.1

Softening Point (ASTM D2398)

Sample	Softening Point C	Softening Point F
6H	51.0	124
6L	50.0	122
8H	49.5	121
8L	46.0	115
12H	46.0	115
12L	44.0	111

TABLE A1 (continued)

Thin Film Oven Test (ASTM D1754)

Sample	Penetration, % of Original	Loss of Wt. (%)	Viscosity (% Increase) 140 F (60.0 C)	Viscosity (% Increase) 275 F (135.0 C)
6H	55.5	0.02	125	54.4
6L	55.8	0.10	171	60.8
8H	66.3	0.51	253	79.3
8L	64.8	0.04	275	50.6
12H	61.7	0.52	273	91.3
12L	68.5	0.42	257	14.5

Solubility in CCL_4 (ASTM D2042)

Sample	% Soluble
6H	99.8
6L	99.7
8H	99.5
8L	99.5
12H	99.5
12L	99.3

Ductility (ASTM D113)

77 F (25.0 C)

All materials exceed 150 cm.

TABLE A2

FINGERPRINT DATA

Card Number	MR&D-5	MR&D-6	MR&D-7
Sample Identification	108	108	116
Project Identification	6H	6L	8H
Composition of asphalt, %			
Fraction A (asphaltenes)	25.3	21.3	27.9
Fraction N (nitrogen bases)	23.5	25.7	18.0
Fraction A_1 (first acidaffins)	17.0	19.6	17.7
Fraction A_2 (second acidaffins)	21.4	23.6	25.3
Fraction P (paraffins)	12.8	9.8	11.1
Wax	0.6	1.8	1.5
$(N + A_1)/(P + A_2)$	1.18	1.36	0.98
N/P	1.84	2.62	1.62
Refractive index of Fraction P (n_D^{25})	1.4861	1.4861	1.4817
Asphalt viscosity at 140 F, P	4122.0	2472.0	3114.0
Penetration at 77 F, 100g, 5 sec.	63.0	61.0	80.0
Maltenes viscosity at 77 F, P	4243.0	17000.0	1669.0
at 140 F, P	41.16	76.48	16.02
at 275 F, cS	50.17	78.74	42.74
Molecular weight of Fraction A	6110.0	4280.0	5910.0
Weight Loss in Thin Film Oven Test, %	0.52	0.04	0.29
Pellet abrasion loss at 77 F			
mg/revolution, unaged	0.108	2.030	0.155
aged 7 days	1.559	3.575	1.538
average of above	0.834	2.802	0.845
unaged	2.72	50.6	3.87
aged 7 days	39.1	89.4	39.0
average of above	20.9	70.0	21.4

TABLE A2 (continued)

Card Number	MR&D-8	MR&D-9	MR&D-10
Sample Identification	122	127	132
Project Identification	8H	12H	12L
Composition of asphalt, %			
Fraction A (asphaltenes)	20.7	26.4	19.8
Fraction N (nitrogen bases)	25.0	17.8	24.4
Fraction A_1 (first acidaffins)	19.6	117.1	19.7
Fraction A_2 (second acidaffins)	24.2	26.2	24.7
Fraction P (paraffins)	10.5	12.5	11.4
Wax	1.9	1.5	2.0
$(N + A_1)/(P + A_2)$	1.29	0.90	1.22
N/P	2.38	1.42	2.14
Refractive index of Fraction P (n_D^{25})	1.4809	1.4808	1.4803
Asphalt viscosity at 140 F, P	1089.0	1476.0	723.0
Penetration at 77 F, 100g, 5 sec.	89.0	116.0	124.0
Maltenes viscosity at 77 F, P	9366.0	1202.0	4920.0
at 140 F, P	57.34	15.29	44.54
at 275 F, cS	67.60	36.34	60.23
Molecular weight of Fraction A	4160.0	5850.0	4350.0
Weight Loss in Thin Film Oven Test, %	0.08	0.50	0.13
Pellet abrasion loss at 77 F			
mg/revolution, unaged	0.600	0.013	0.091
aged 7 days	2.638	0.200	1.062
average of above	1.619	0.106	0.576
unaged	15.0	0.33	2.28
aged 7 days	65.9	4.99	26.4
average of above	40.4	2.66	14.4

APPENDIX B
AGGREGATE PROPERTIES

Unless otherwise stated or required by standard methods all tests were performed on each sieve size fraction of aggregate.

1. Los Angeles Abrasion (per cent wear), (ASTM C131)

Grading	Wear after 100 rev., %	Wear after 500 rev., %
B	9.9	39.4
C	9.7	37.5
D	9.9	35.0

2. Deleterious Materials

   A. Friable particles, ocher, and shells by visual inspection of hand specimens: None

   B. Soft or nondurable particles (AASHTO T189):

Size	Sample wt. (g)	Number of Particles	% by wt. Soft Particles
3/4 - 1/2	600.5	124	0
1/2 - 3/8	202.1	95	0

   C. Chert (less than 2.45 specific gravity). Test methods by visual count and heavy media separation. Heavy liquid consisted of 1,1,2,2-Tetrabromoethane (acetylene Tetrabromide) and carbon tetrachloride in proportions to provide specific gravity by hydrometer of 2.450 ± 0.002. Proportions were continually adjusted to make up evaporation losses.

Size	Sample wt. (g)	Wt. particles less than 2.45 S.G.	No. particles less than 2.45 S.G.	% by wt. less than 2.45 S.G.
3/4 - 1/2	867.6	15.5	3	1.79
1/2 - 3/8	515.9	0	0	0
3/8 - 4	315.1	0	0	0
4 - 8	279.5	0	0	0

3. Soundness; five cycles, sodium sulfate (AASHTO T104).

Three gradations were selected as being representative of the final project mixtures. These gradations follow the mid-specification for dense (IVb), coarse (IIIc) and fine (Vb) as shown by The Asphalt Institute.

Gradation	Coarse Agg. (+ No. 4) % Loss	Fine Agg. (- No. 4) % Loss
Coarse	9.0	4.7
Dense	11.0	4.6
Fine	8.3	4.0

4. Specific Gravity and Absorption (ASTM C127, C128, D854).

Size Fraction	G_{BULK}	G_{BSSD}	G_{APP}	% ABS
3/4 - 1/2	2.543	2.598	2.689	2.135
1/2 - 3/8	2.497	2.564	2.678	2.707
3/8 - 4	2.514	2.586	2.708	2.852
4 - 8	2.569	2.643	2.772	2.849
8 - 16	2.599	2.672	2.802	2.798
16 - 30	2.692	2.729	2.795	1.358
30 - 50	2.753	2.775	2.816	0.806
50 - 100	2.671	2.699	2.747	1.024
100 - 200	2.778	2.793	2.822	0.570
Filler	---	---	2.860	---

Values shown are averages based on multiple measurements; following table shows the number of observations and standard deviation based on the range of values. Test sequence for coarse and fine aggregates was determined by application of random numbers to each sample of each fraction. All values were checked for outliers according to ASTM E178 and in some cases data were rejected when necessary.

Size	No. Tests	Standard Deviations G_B	G_{BSSD}	G_{APP}	% ABS
3/4 - 1/2	2	0	0	0.004	0.048
1/2 - 3/8	2	0	0	0.004	0.087
3/8 - 4	3	0.012	0.007	0.007	0.250
4 - 8	3	0.007	0.005	0.002	0.079
8 - 16	4	0.010	0.010	0.014	0.105
16 - 30	4	0.021	0.022	0.023	0
30 - 50	3	0.002	0.001	0.001	0.024
50 - 100	5	0.007	0.078	0.083	0.501
100 - 200	3	0.002	0.002	0.003	0.048
Filler	4	---	---	0.006	---

5. Flakiness Index and Sphericity

Flakiness index and sphericity are not specification tests but the measured values are included for future reference and comparison. Flakiness Index is as defined by The Asphalt Institute. Sphericity is as defined by Krumbein and Pettijohn except that particle volume was determined using weight and apparent specific gravity instead of direct volume measurement. Sphericity is defined as:

$$\phi = \frac{d_n}{D_s}.$$

where ϕ = sphericity

d_n = diameter of a sphere of the same volume as the particle.

D_s = diameter of a sphere that would enclose the particle.

Size	No. Particles	Flakiness Index	Sphericity No. Particles	Sphericity Avg.	Sphericity Std. Dev.
3/4 - 1/2	300	15.2	50	0.634	0.072
1/2 - 3/8	300	11.3	50	0.639	0.071
3/8 - 4	300	25.8	50	0.585	0.086

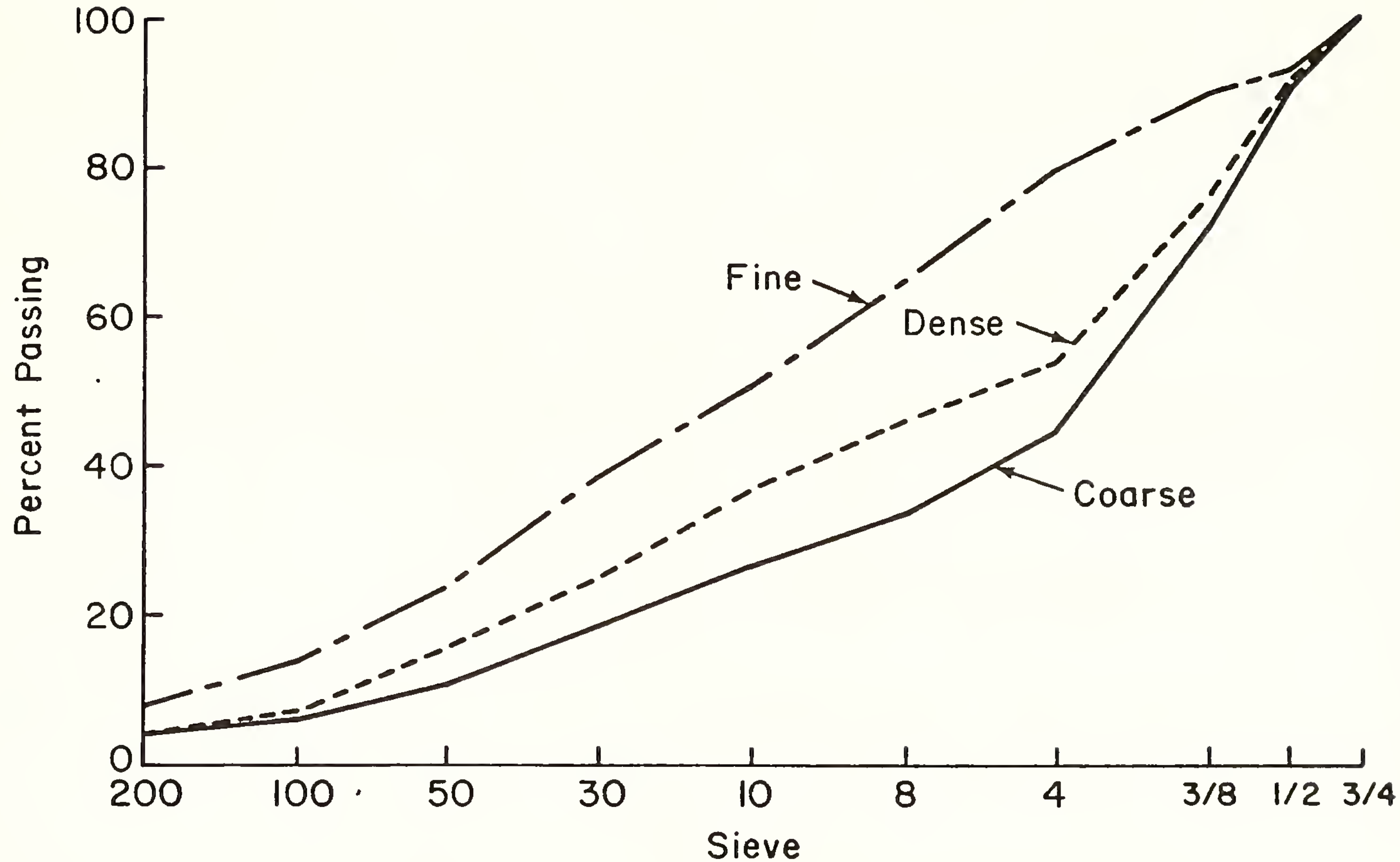

Fig. B1 MIXTURE GRADATIONS.

APPENDIX C
MIXTURE PROPERTIES

TABLE C1
SUMMARY OF MIXTURE PROPERTIES

Property/Mixture	6HC	6HD	6HF	6LC	6LD	6LF
% Asph. by wt. agg.	6.8	6.8	6.9	6.8	6.8	6.9
% Asph. by wt. mix	6.37	6.37	6.45	6.37	6.37	6.45
% Agg.	93.63	93.63	93.55	93.63	93.63	93.55
Mix bulk sp. gr.	2.401	2.376	2.390	2.401	2.376	2.390
Absorbed Asph. (%)	2.339	1.972	1.452	2.339	1.972	1.452
Agg. bulk sp. gr.	2.582	2.601	2.648	2.582	2.601	2.648
Asph. sp. gr.	1.028	1.028	1.028	1.028	1.028	1.028
% Effective Asph.	4.180	4.524	5.092	4.180	4.524	5.092
VMA (%)	12.9	14.5	15.6	12.9	14.5	15.6
Air voids (%)	3.2	4.0	3.7	3.2	4.0	3.7
Stability	42.0	46.0	42.0	45.0	48.0	45.0
Cohesiometer	277.0	390.0	268.0	335.0	359.0	303.0

Property/Mixture	8HC	8HD	8HF	8LC	8LD	8LF
% Asph. by wt. agg.	6.8	6.8	6.9	6.8	6.8	6.9
% Asph. by wt. mix	6.37	6.37	6.45	6.37	6.37	6.45
% Agg.	93.63	93.63	93.55	93.63	93.63	93.55
Mix bulk sp. gr.	2.401	2.376	2.390	2.401	2.376	2.390
Absorbed Asph. (%)	2.339	1.972	1.452	2.339	1.972	1.452
Agg. bulk sp. gr.	2.582	2.601	2.648	2.582	2.601	2.648
Asph. sp. gr.	1.031	1.031	1.031	1.027	1.027	1.027
% Effective Asph.	4.180	4.524	5.092	4.180	4.524	5.092
VMA (%)	12.9	14.5	15.6	12.9	14.5	15.6
Air voids (%)	3.2	4.0	3.8	3.2	4.0	3.7
Stability	45.0	47.0	43.0	47.0	46.0	45.0
Cohesiometer	387.0	435.0	344.0	334.0	378.0	351.0

TABLE C1 (continued)

Property/Mixture	12HC	12HD	12HF	12LC	12LD	12LF
% Asph. by wt. agg.	6.8	6.8	6.9	6.8	6.8	6.9
% Asph. by wt. mix	6.37	6.37	6.45	6.37	6.37	6.45
% Agg.	93.63	93.63	93.55	93.63	93.63	93.55
Mix bulk sp. gr.	2.401	2.376	2.390	2.401	2.376	2.390
Absorbed Asph. (%)	2.339	1.972	1.452	2.339	1.972	1.452
Agg. bulk sp. gr.	2.582	2.601	2.648	2.582	2.601	2.648
Asph. sp. gr.	1.027	1.027	1.027	1.026	1.026	1.026
% Effective asph.	4.180	4.524	5.092	4.180	4.524	5.092
VMA (%)	12.9	14.5	15.6	12.9	14.5	15.6
Air voids (%)	3.2	4.0	3.7	3.2	4.0	3.7
Stability	41.0	46.0	40.0	44.0	43.0	41.0
Cohesiometer	413.0	349.0	405.0	377.0	323.0	379.0

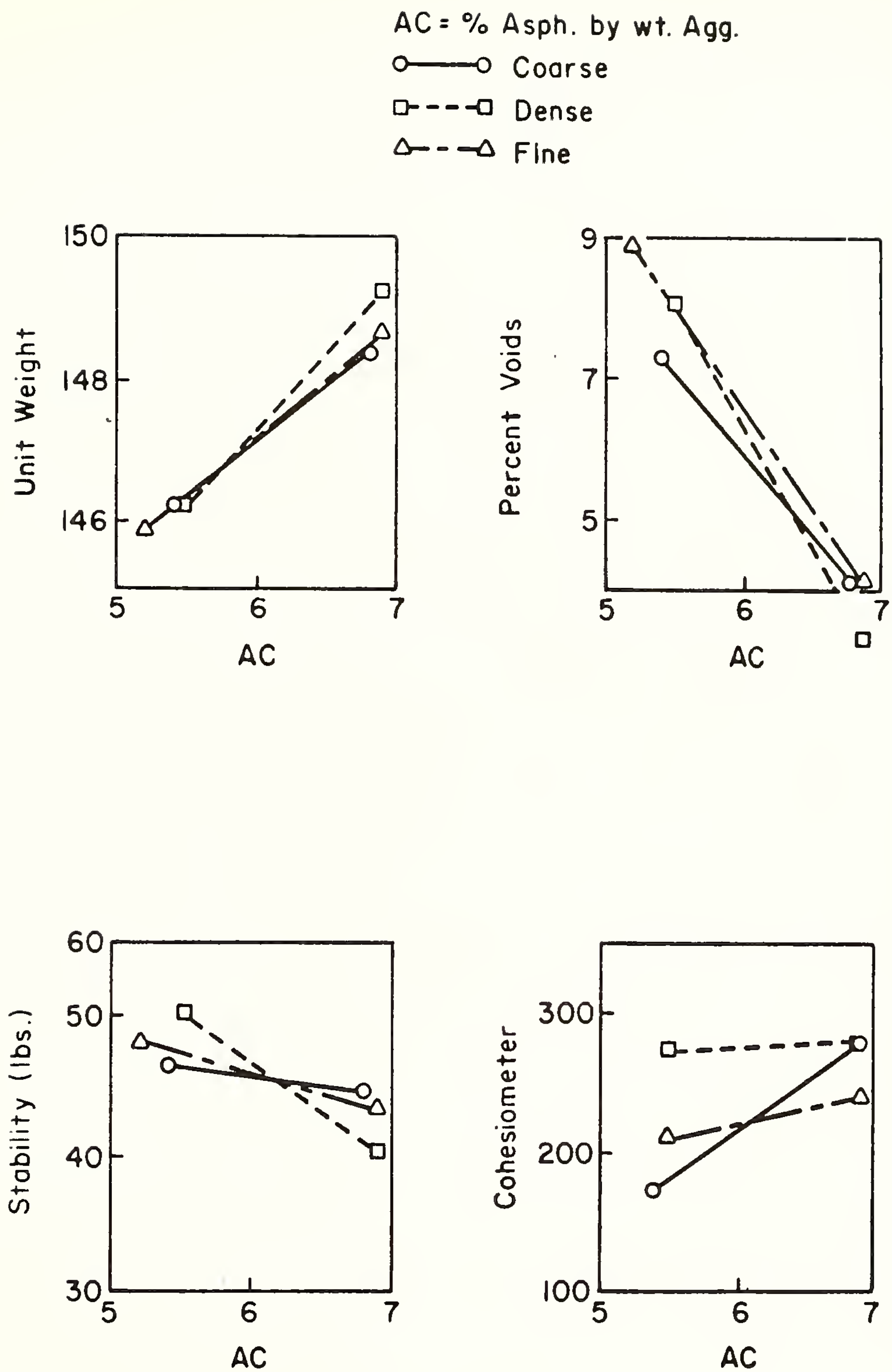

Fig. C1 MIXTURE PROPERTIES.

APPENDIX D

TEST EQUIPMENT

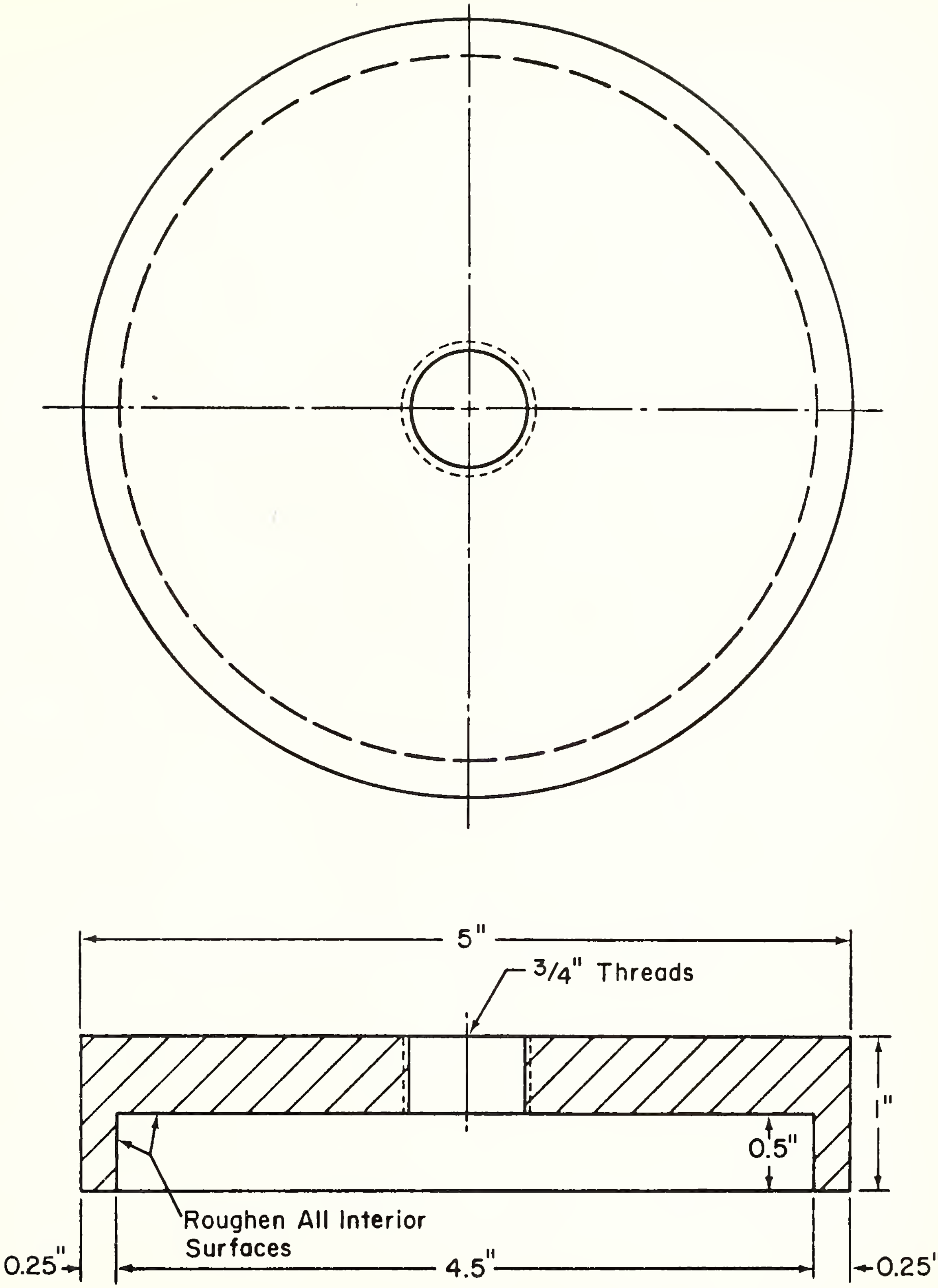

Fig. D1 CAP DETAIL.

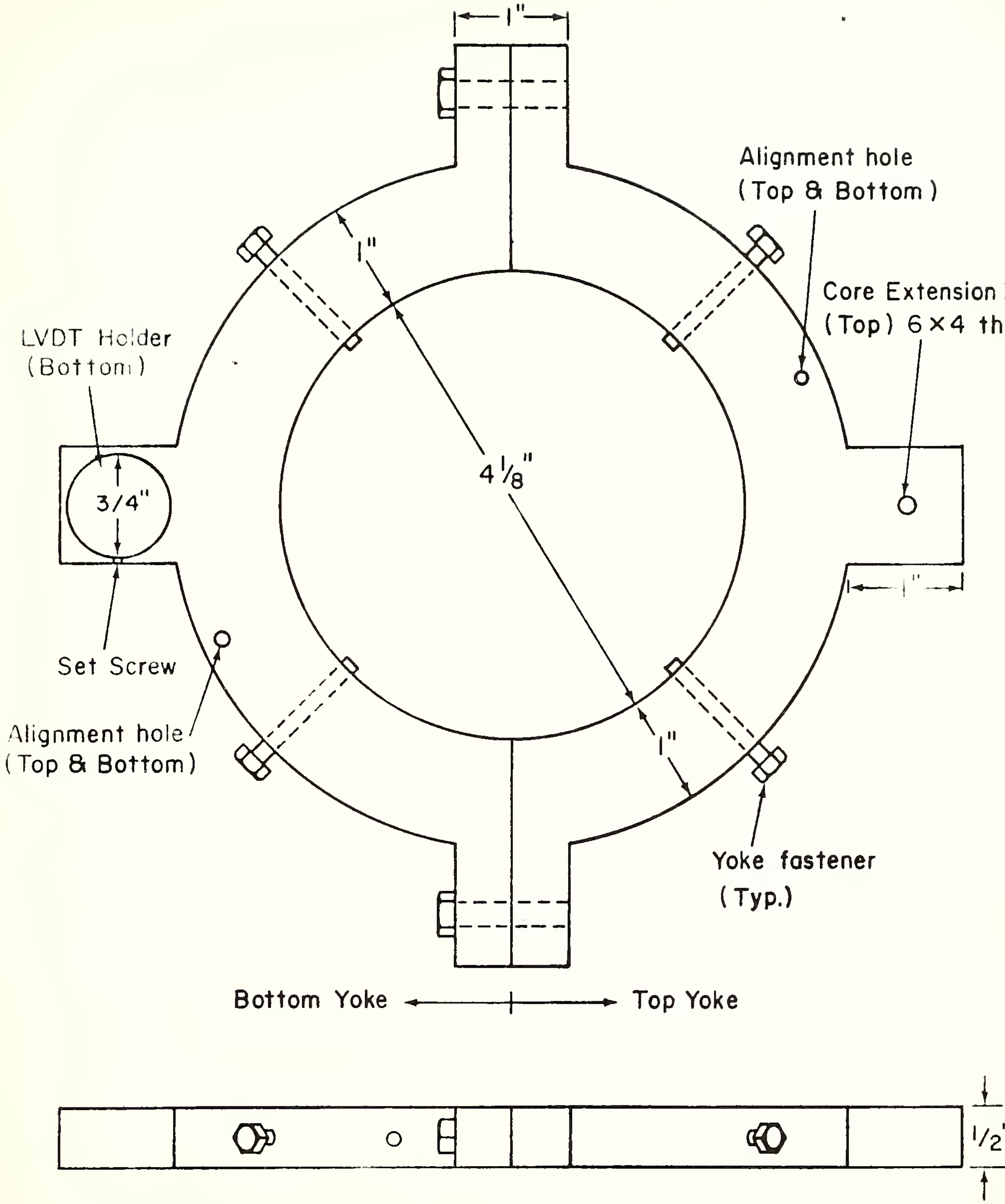

Fig. D2 LVDT YOKES.

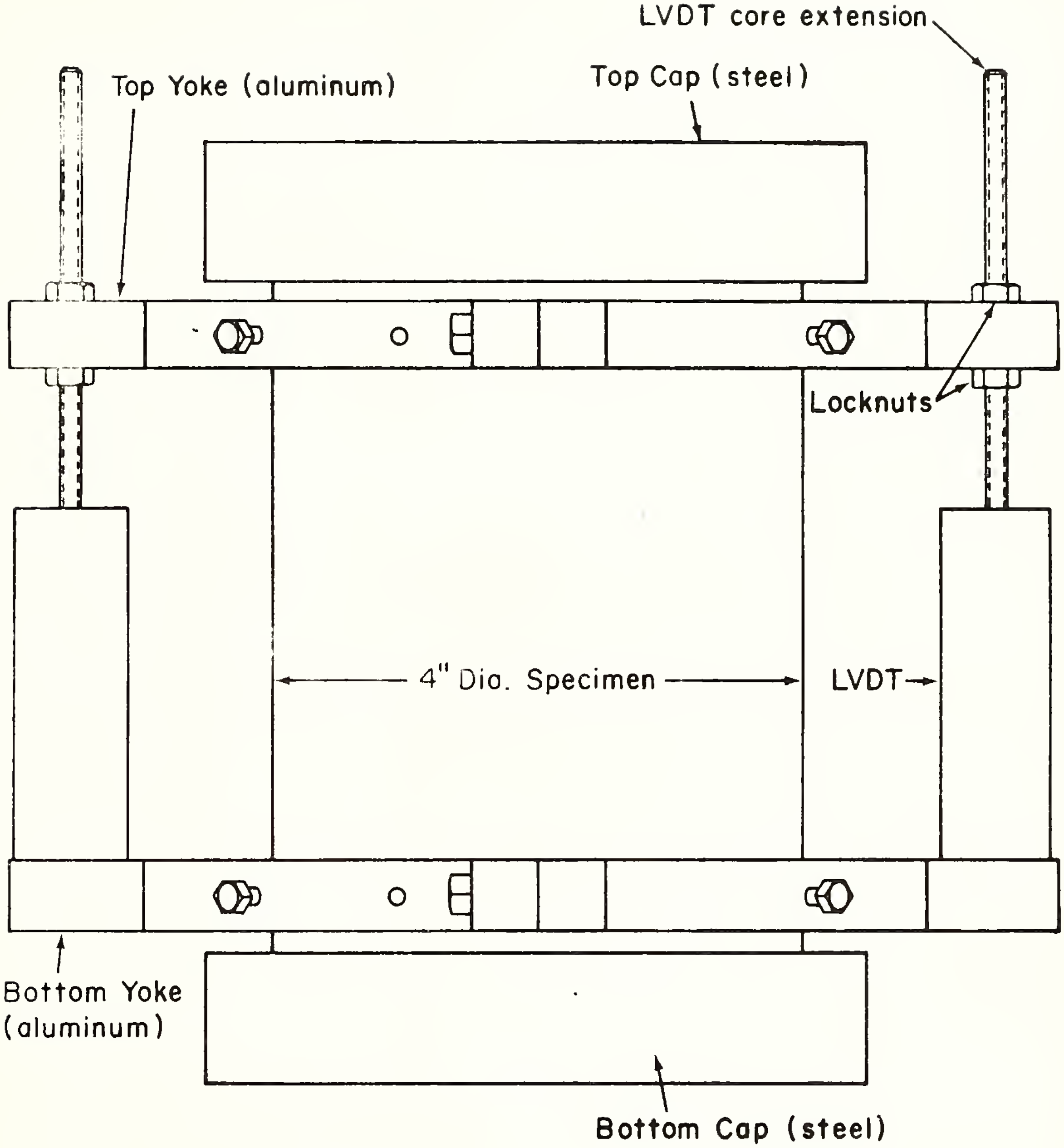

Fig. D3 TEST SET-UP.

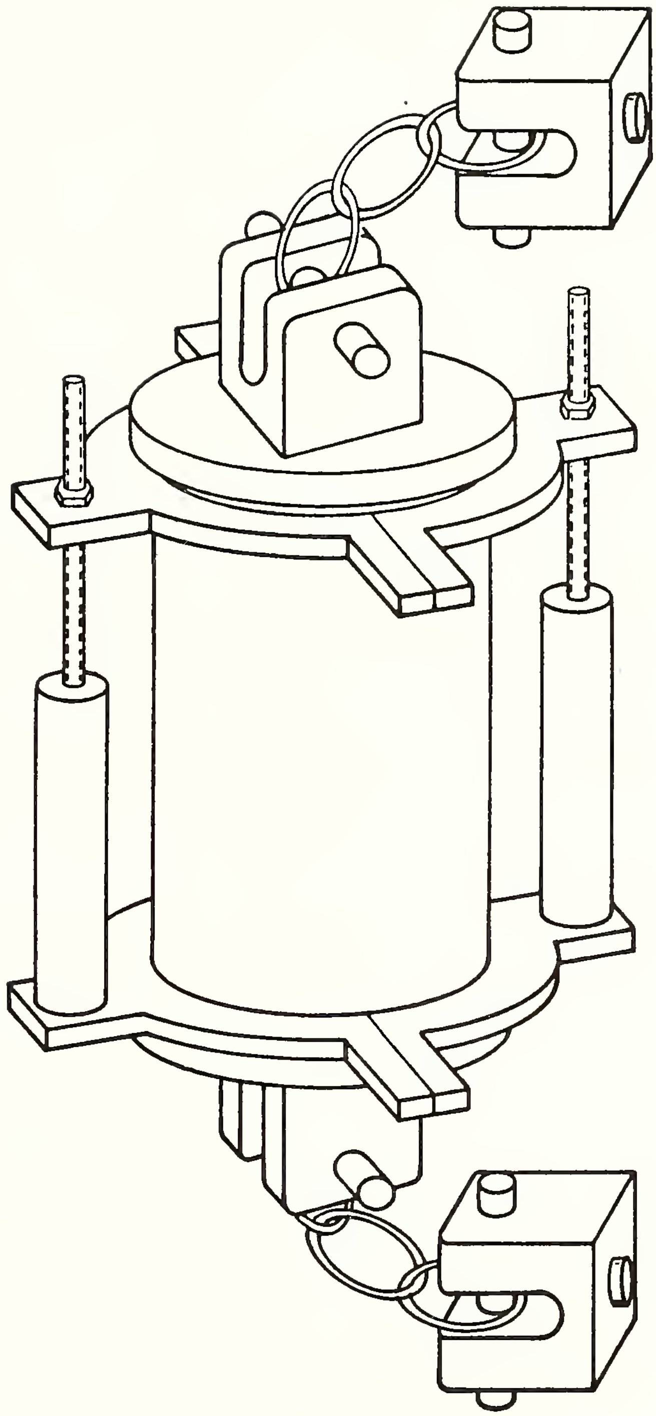

Fig. D4 TEST SET-UP.

TABLE 1

CELL DESIGNATIONS, NUMBER OF OBSERVATIONS PER CELL AND CELL MEANS

		Temperature (F)					
		-17.5	14	45.5	77	108.5	140
MIX TYPE	6LD	1 4 28			G 4 3770	6 4 4949	M 3 17,404
	6HD				I 4 4900		N 4 16,415
	8LD	A 4 51	B 8 274	C 4 2953	D 11 3640	E 3 5120	P 4 9,564
	8HD				F 4 4065		Q 3 14,371
	12LD	2 4 33			H 4 3252	7 4 5593	R 2 11,086
	12HD				J 4 4003		S 4 13,398
	8LF	8 4 44			K 4 5488	3 4 6200	T 3 17,675
	8LC	4 4 38			L 4 4097	5 4 5539	U 3 6,859

Cell → | 1 4 | ← No. obs.
| 28 | ← $\overline{\varepsilon}_f$ (MII)

TABLE 2

CELL STANDARD DEVIATIONS IN MII

		Temperature (F)					
		-17.5	14	45.5	77	108.5	140
MIX TYPE	6LD	1 18			G 583	6 2331	M 5308
	6HD				I 1199		N 3768
	8LD	A 46	B 423	C 175	D 1060	E 1059	P 4069
	8HD				F 262		Q 5967
	12LD	2 21			H 972	7 1616	R 5784
	12HD				J 914		S 6515
	8LF	8 13			K 1017	3 1139	T 9157
	8LC	4 9			L 451	5 2776	4 4881

TABLE 3

EXPLORATORY EXPERIMENT

ANOVA

Source	df	SS	MS	F
Mix	7	1.317 E07	1.881 E06	2.96
Error	24	1.528 E07	6.366 E05	
Total	31	2.844 E07		

$F_{0.05} = 2.42$

$F_{0.01} = 3.50$

TABLE 4

CELLS FOR EFFECT OF MIXTURE TYPE AND TEMPERATURE

Temp / Mix	-17.5	77	108.5
6LD	1	G	6
8LD	A	D	E
12LD	2	H	7
8LF	8	K	3
8LC	4	L	5

TABLE 5

EFFECT OF MIXTURE TYPE AND TEMPERATURE

ANOVA

Source	df	SS	MS	F
Mix	4	616.7	154.2	2.20
Temp	2	50,453.0	25,226.5	359.27
Mix×Temp	8	301.8	50.2	0.72
Error	51	3,581.0	70.2	

CRITICAL F VALUES

Source	∇_1	∇_2	$\alpha = 0.05$	$\alpha = 0.01$
Mix	4	51	2.57	3.73
Temp	2	51	3.19	5.07
Mix×Temp	8	51	2.14	2.90

TABLE 6

CELLS FOR EFFECT OF GRADATION

Temp / Mix	-17.5	77	108.5	140
8LD	A	D	E	P
8LF	8	K	3	T
8LC	4	L	5	4

TABLE 7

EFFECT OF GRADATION AND TEMPERATURE

ANOVA

Source	df	SS	MS	F
Mix	2	44.18	22.09	5.24
Temp	3	2034.15	678.05	160.86
Mix×Temp	6	54.20	9.03	2.14
Error	40	168.61	4.22	

CRITICAL F VALUES

Source	∇_1	∇_2	$\alpha = 0.05$	$\alpha = 0.01$
Mix	2	40	3.23	5.18
Temp	3	40	2.84	4.31
Mix×Temp	6	40	2.34	3.29

TABLE 8

CELLS FOR FINAL ANALYSIS

Mix \ Temp	-17.5	77	108.5	140
6LD	1	G	6	M
8LD	A	D	E	P
12LD	2	H	7	R
8LF	8	K	3	T
8LC	4	L	5	4

TABLE 9

FINAL ANALYSIS

ANOVA

Source	df	SS	MS	F
Mix	4	5.9	1.5	2.79
Temp	3	624.3	208.1	390.71
Mix×Temp	12	12.7	1.1	1.98
Error	61	32.5	0.5	

CRITICAL F VALUES

Source	∇_1	∇_2	$\alpha = 0.05$	$\alpha = 0.01$
Mix	4	61	2.53	3.65
Temp	3	61	2.76	4.16
Mix×Temp	12	61	1.92	2.50

TABLE 10

REGRESSION COEFFICIENTS FOR CASE I

Fit	B_0	B_1	B_2	B_3	Mult. R	Cumul. R^2
Cubic	-439.4	104.5	-1.470	0.0084	0.83	0.70
Quadratic	369.1	-33.52	0.6923	0	0.83	0.68
Linear	-1981	78.05	0	0	0.76	0.57

TABLE 11

REGRESSION COEFFICIENTS FOR CASE II

Fit	B_0	B_1	B_2	B_3	Mult. R	Cumul. R^2
Cubic	2.049	0.0887	-0.0004	0	0.95	0.91
Quadratic	2.176	0.0675	-0.0001	0	0.95	0.91
Linear	2.511	0.0511	0	0	0.95	0.90

TABLE 12

REGRESSION COEFFICIENTS FOR CASES III AND IV

	Case III	Case IV
β_0	-414.5	2.059
β_1	75.04	0.0316
β_2	-0.1745	-0.0001
β_3	0.0002	0
β_4	72.21	0.0748
β_5	-1.421	-0.0004
β_6	0.0092	0
β_7	-0.4604	-0.0002
β_8	0.0001	0
β_9	0	0
Mult. R	0.83	0.96
Cumul. R^2	0.71	0.91

TABLE 13

REGRESSION COEFFICIENTS FOR
CASES V, VI AND VII

	Case V	Case VI	Case VII
B_o	83.22	---	---
B_1	-1.123	-124.6	40.12
B_2	0.007534	8480	24.45
B_3	253.3	1.198 E-05	14.73
B_4	---	---	4.920

TABLE 14

COMPARISON OF MEASURED (S_C) AND THEORETICAL (S_T) MIXTURE STIFFNESS

Mix	Temp (F)	No. Specimens	No. Points	Avg. S_C/S_T
8LD	108.5	3	13	0.9
"	77	11	59	2.2
"	45.5	4	25	2.7
"	14	8	42	1.8
"	-17.5	4	13	1.3
8LF	108.5	4	21	0.6
"	77	4	26	3.8
"	-17.5	4	16	1.9
8LC	108.5	4	5	0.2
"	77	4	24	2.2
"	-17.5	4	22	2.1
8HD	77	4	25	2.8
6LD	108.5	4	4	4.2
"	77	4	24	3.6
"	-17.5	4	15	3.5
6HD	77	4	22	1.3
12LD	108.5	4	4	2.6
"	77	4	23	2.1
"	-17.5	4	18	5.3
12HD	77	4	25	1.4
Totals		90	426	
Avg.				2.3

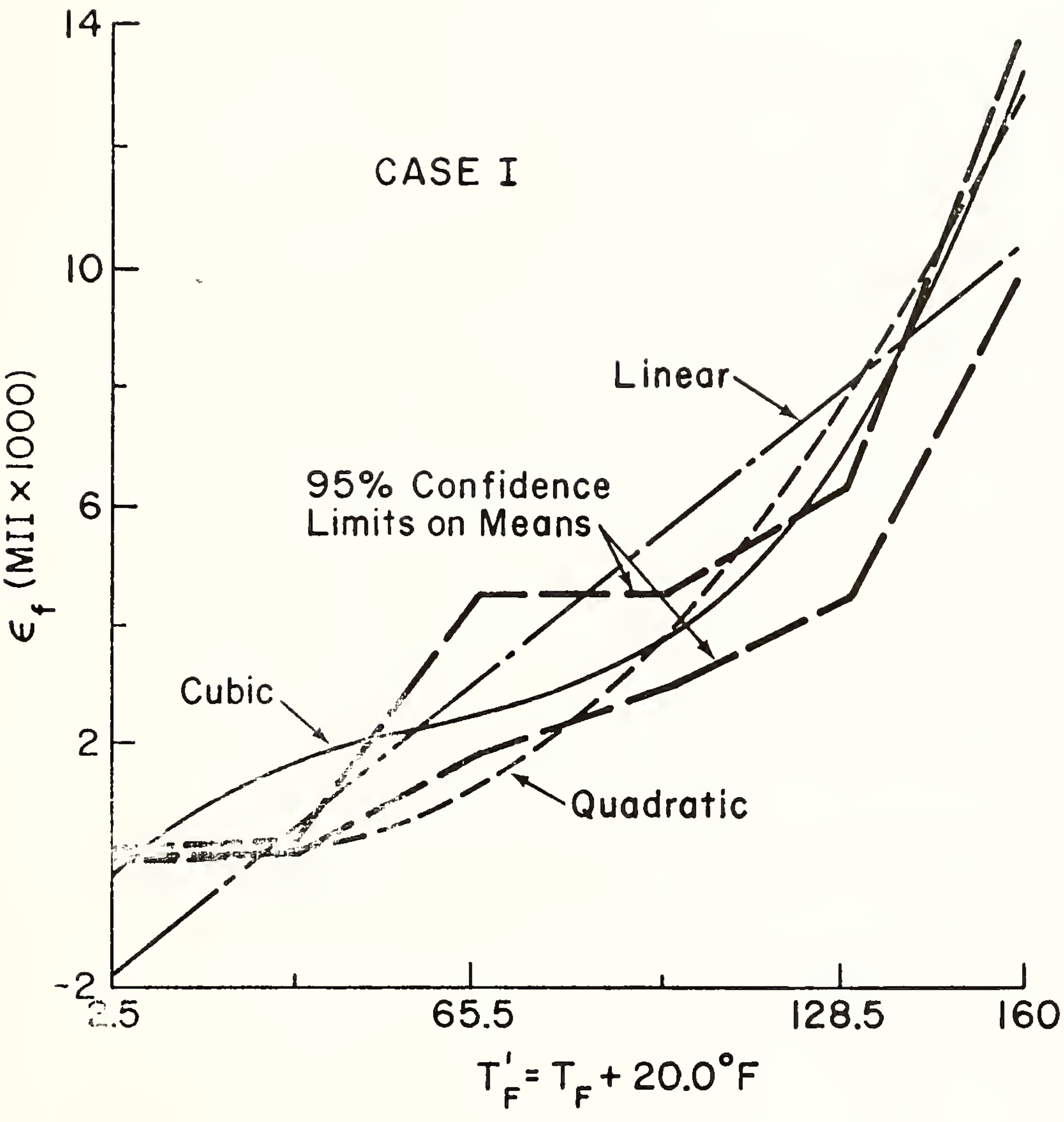

Fig. 1 LINEAR REGRESSION FITS AND 95 % CONFIDENCE LIMITS ON MEANS.

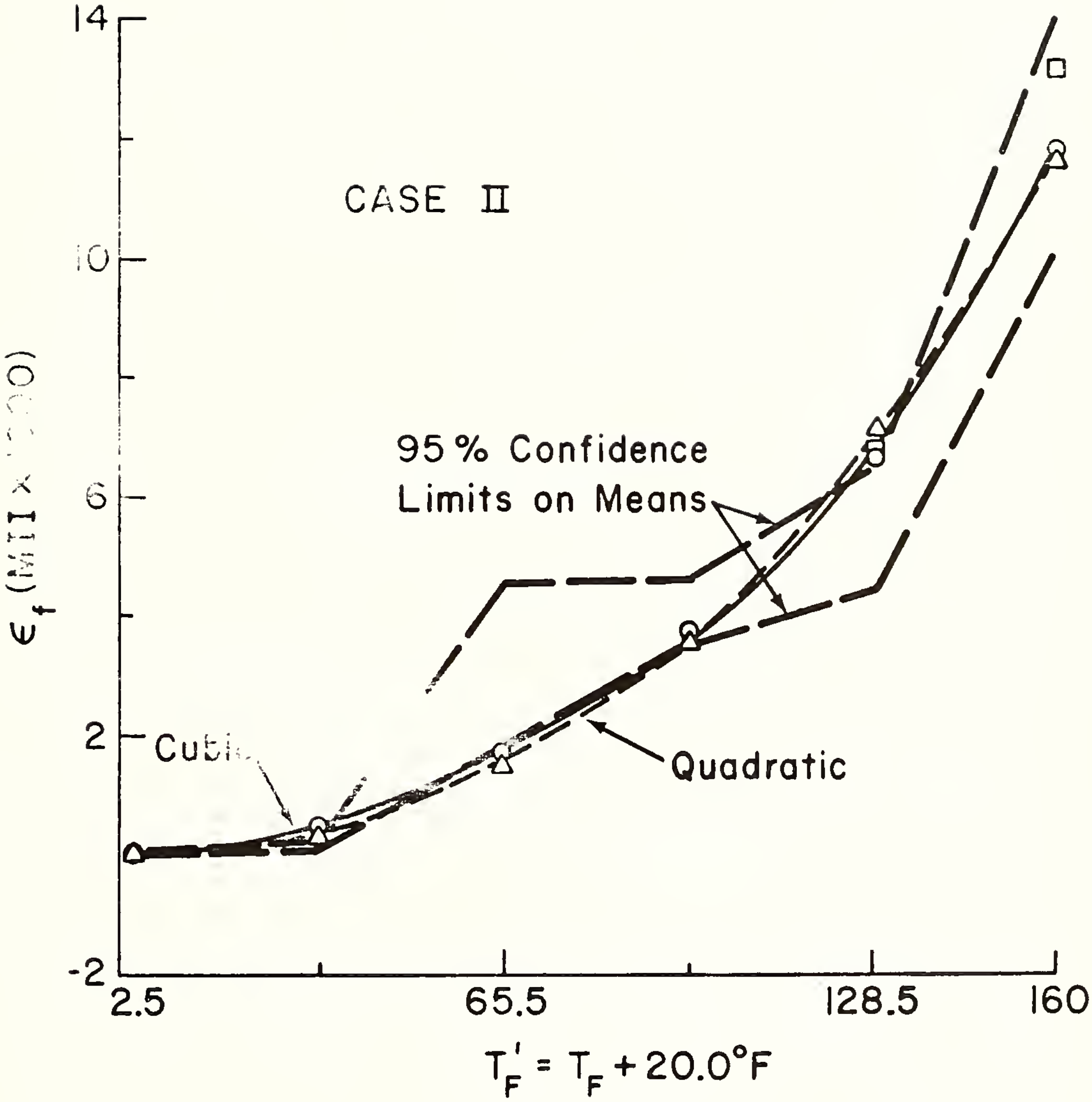

Fig. 2 LINEAR REGRESSION FITS AND 95% CONFIDENCE LIMITS ON MEANS.

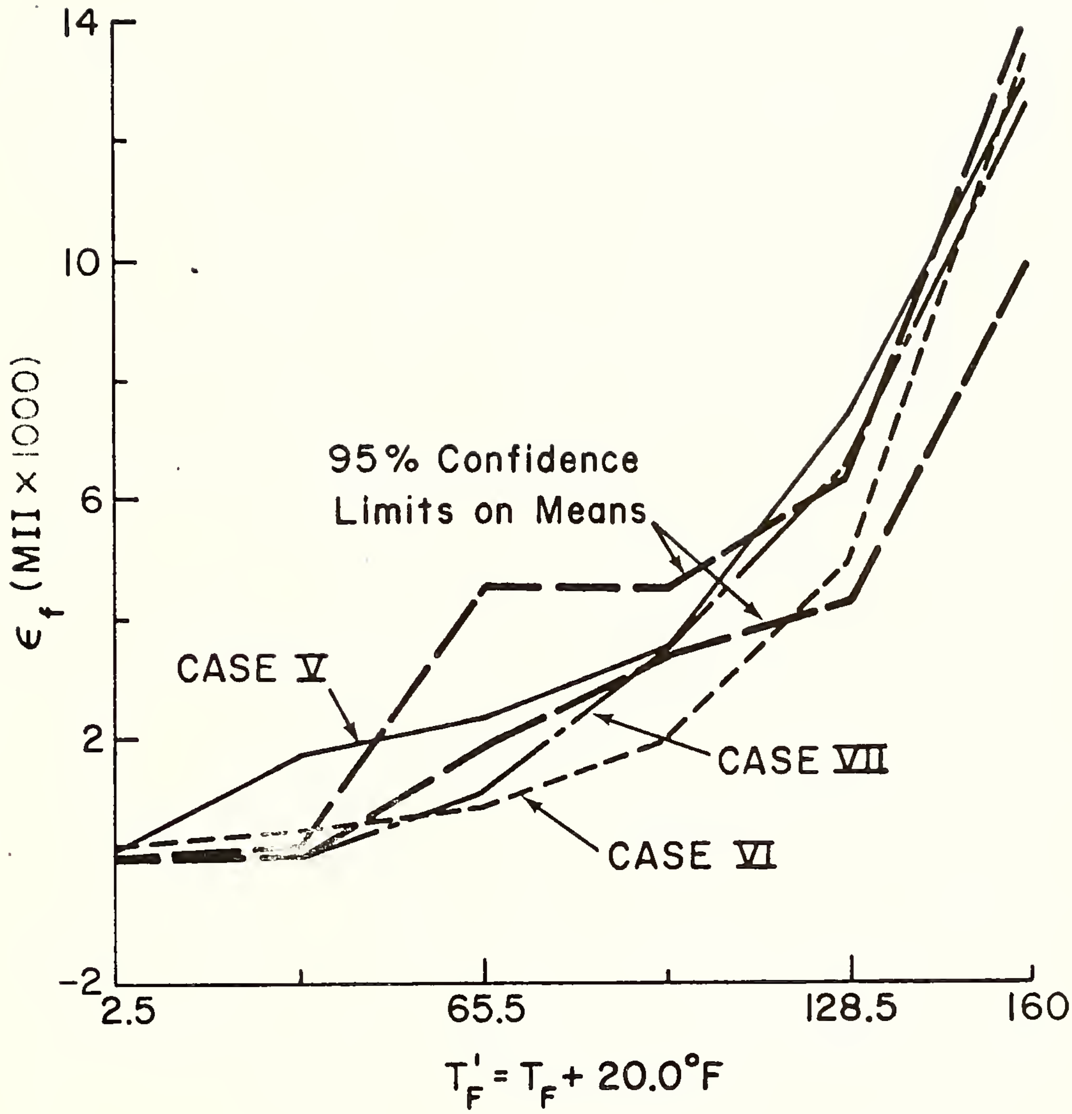

Fig. 3 NON-LINEAR FITS AND 95% CONFIDENCE LIMITS ON MEANS.

COVER DESIGN BY ALDO GIORGINI